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Submicrosecond Comparisons of Time Standards via the Navigation Technology Satellites (NTS)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During May through September 1978 a six nation cooperative experiment was performed to intercompare time standards of major laboratories at the submicrosecond level using NTS satellites.

NTS time transfer receivers, which were developed for use with the NTS series of satellites, were installed at the Division of National Mapping (DNM), Australia; in Japan at the Radio Research Laboratories (RRL) and the National Research Laboratory of Metrology (NRLM); National Research Council (NRC), Canada; Royal Greenwich Observatory (RGO), England; Bureau International de l'Heure, France (BIH); Institute for Applied Geodesy (IFAG), West Germany; and in the

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20. Abstract (Continued)

U.S. at the Goddard Space Flight Center (GSFC), National Bureau of Standards (NBS), Naval Research Laboratory (NRL), and the Naval Observatory (USNO).

The results obtained by satellite were compared to those obtained by portable clocks. At all stations the differences were less than 0.75 μs. The RMS of the data from nine stations is less than 0.4 μs.

CONTENTS

SUBMICROSECOND COMPARISONS OF TIME STANDARDS VIA THE NAVIGATION TECHNOLOGY SATELLITES (NTS)

INTRODUCTION

The major objective of the experiment was to perform an interim demonstration of the time transfer capability of the NAVSTAR GPS system using a single NTS satellite. Measurements of time difference are made from the NTS tracking network and at the participating observatories. The NTS network measurements are used to compute the NTS orbit trajectory. The central NTS tracking station has a time link to the Naval Observatory UTC(USNO,MC1) master clock. Using measurements taken with the NTS receiver at the remote observatory, the time transfer value UTC(USNO,MC1) − UTC(REMOTE, VIA NTS) is calculated. The goal for the NTS effort was to achieve worldwide time transfer of less than 1.0 μs accuracy. Comparison of the satellite measurements to travelling clock observations showed differences no greater than 0.7 μs.

A second objective was to compute weekly worldwide intercomparisons of the observatory clock offsets using predicted values of satellite clock offset and ephemeris. Each participant entered appropriate measurements into computer files for later processing. Other objectives include colocation at laser sites and the use of the observatory time scales in evaluating the spacecraft clock performance.

For GPS, a similar procedure could be followed using simultaneous measurements taken between the user and four GPS satellites. With the four GPS pseudo-range (time difference) measurements taken at an unknown location the user may solve for three position coordinates in addition to time offset with respect to GPS time.

TIME DIFFERENCE MEASUREMENTS

Time difference (pseudo-range) measurements are made between the spacecraft and the user by side tone ranging [1]. The NTS-2 spacecraft also has a GPS pseudo-random sequence transmitter. All measurements presented in this paper were made using the side tone ranging system, which has a resolution of 1.56 ns (48 cm). Measurements of time difference may be converted to pseudo-range by multiplying by the speed of light in a vacuum. Units of time are used in this report to facilitate comparisons with the PTTI community.

The time difference measurement is composed of the difference between the satellite clock and the user clock, plus satellite transmitter delays, propagation path delay, ionospheric delay, tropospheric delay, user antenna delay, cable delay, and receiver delay. All of these factors must be measured or estimated. In addition to the above factors, the

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spacecraft clock is influenced by the relativistic frequency shift, magnetic fields, energetic particles, and small variations in temperature and drive level.

Receivers of two designs were employed in making the measurements. One receiver [2] made measurements at a nominal UHF frequency of 335 MHz. The second receiver was capable of making measurements at the L band frequency of 1580 MHz in addition to the UHF frequency. The two channel receiver measurements were combined, by software, to correct for the first order ionospheric refraction.

SPACECRAFT FREQUENCY STANDARDS

Timing signals transmitted from NTS-2 are derived from a cesium frequency standard; NTS-1 employs both rubidium and quartz oscillators. Frequency stability results have been previously reported [3,4] for one of the NTS-2 cesium standards and for rubidium and quartz oscillators.

The NTS-2 cesium standard was used to measure the relativistic frequency shift [5] at the GPS constellation altitude. The NTS-2 cesium output frequency was adjusted so that the received frequency is near that of UTC(USNO,MC1). In contrast, the NTS-1 quartz oscillator is periodically adjusted in frequency and time. The maximum frequency excursions of the quartz varied from $+ 2 \times 10^{-9}$ to $- 4 \times 10^{-9}$ with respect to UTC(USNO, MC1). Noteworthy is the fact that the ease of operation is superior with cesium, inasmuch as comparatively large periodic adjustments are required with the quartz frequency standard.

TIME TRANSFER TECHNIQUES

The time transfer to a remote location is obtained by four time links to UTC(USNO, MC1). The four links are (a) from the remote user clock to the spacecraft clock, (b) the spacecraft frequency time update for the time difference between observations obtained at the remote site and the central site, (c) from the central station clock to the spacecraft clock, and (d) from the central station clock to UTC(USNO,MC1). Figure 1 depicts the four links used in this procedure. This procedure incorporates the short to medium term stability of the spacecraft and control station clock with the long term stability of the U.S. Naval Observatory multi-clock time scale.

Measurements of [UTC(USNO,MC1)-UTC(REMOTE, VIA NTS)] may be taken with a variety of frequency sources of varying stability. The major observatories participating in this experiment possess frequency standards and time scales of proven accuracy, with sufficient difference in geographic location (Fig. 2), to check the time transfer at different positions of the spacecraft orbit.

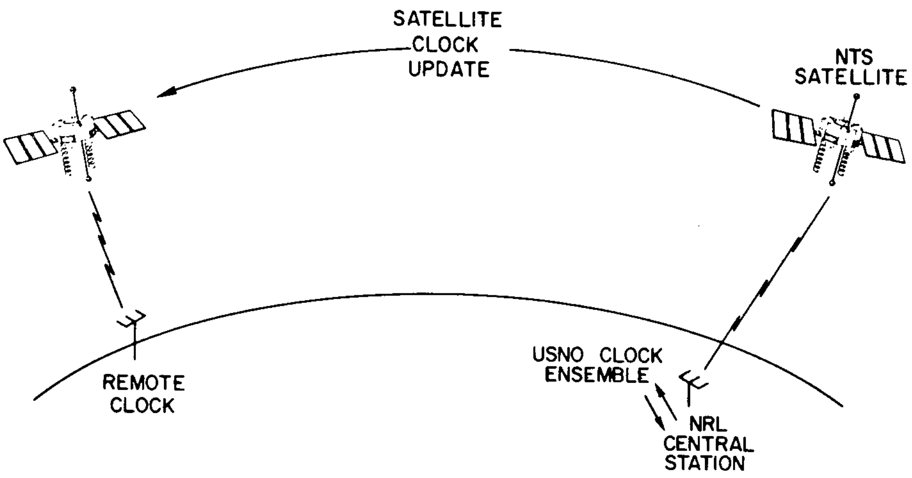

Fig. 1 — Time transfer configuration

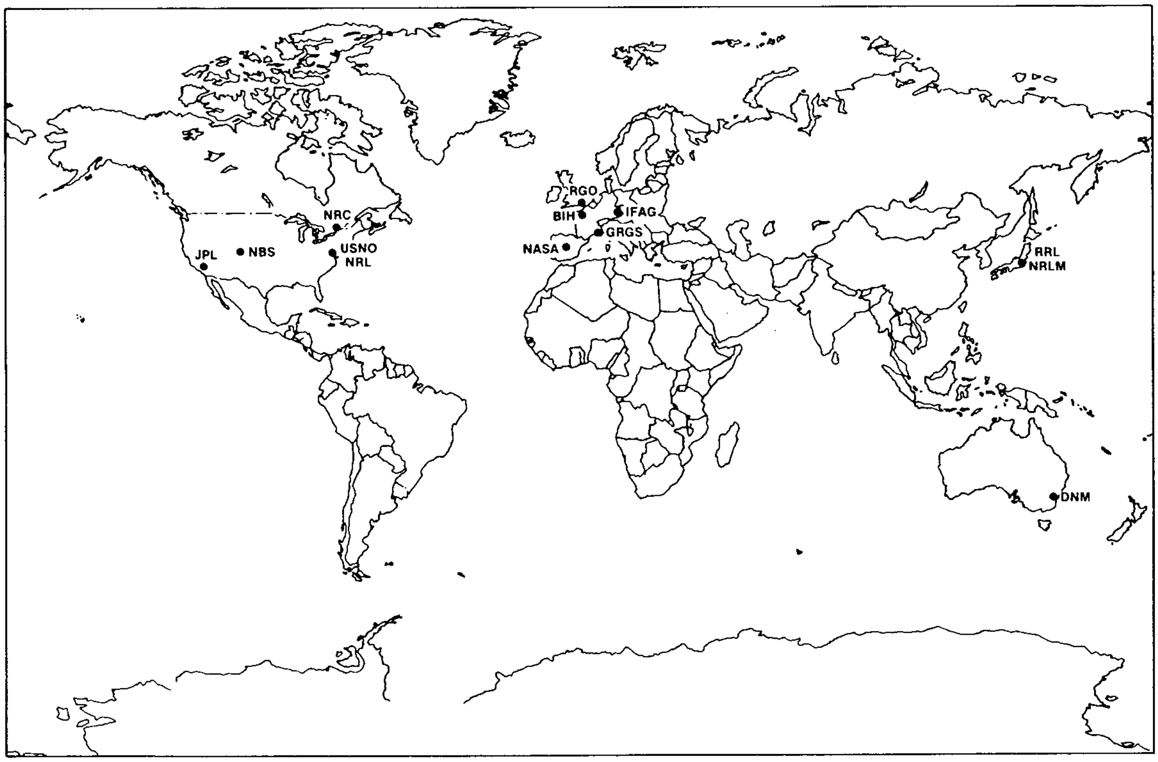

Fig. 2 — International time synchronization via Navigation Technology Satellite

TIME TRANSFER RESULTS

Figures 3 through 12 present time transfer results as determined from the NTS spacecraft. The figures are similar in format inasmuch as each remote observing station is referenced through the NTS central ground observing station located at Chesapeake Bay Division (CBD) of NRL. The CBD site is linked to the USNOMC by a series of portable clock closures to an accuracy of 10 to 20 ns.

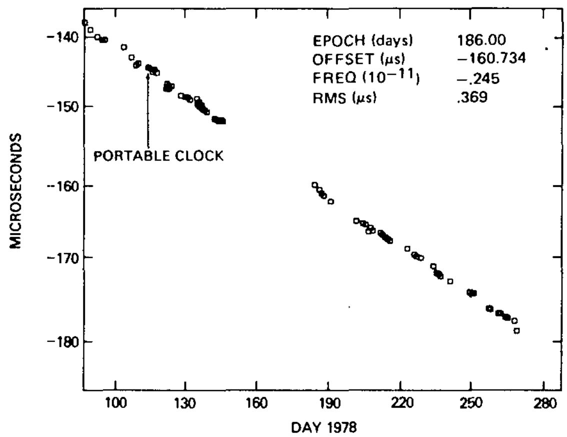

Fig. 3 — Time transfer results from Royal Greenwich Observatory (USNO,MC1)-(RGO,JP)

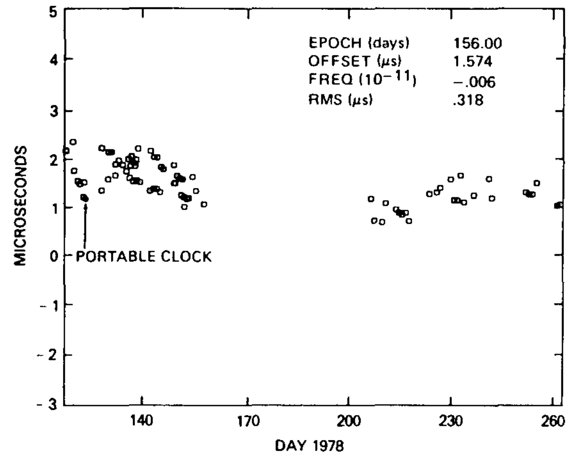

Fig. 4 — Time transfer results from Paris OP (USNO,MC1)-(OP)

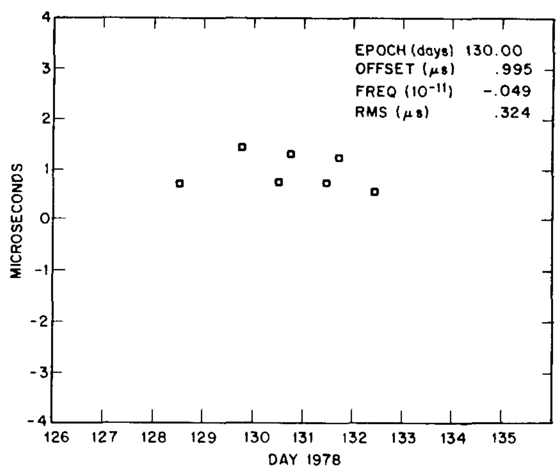

Fig. 5 — Time transfer results from Cerga, France (USNO,MC1)-(CERGA)

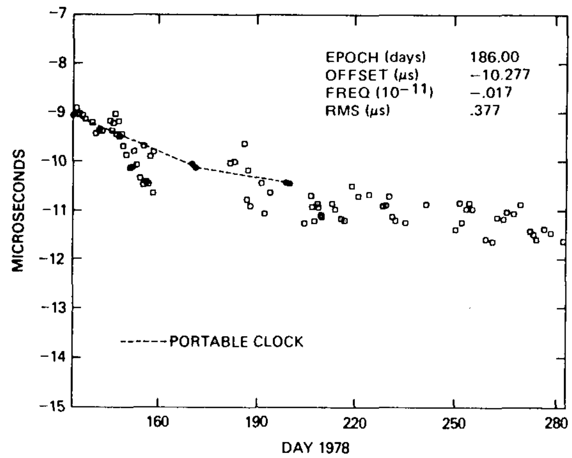

Fig. 6 — Time transfer results from the Institute for Applied Geodesy, Wettzell, West Germany (USNO,MC1)-(IFAG)

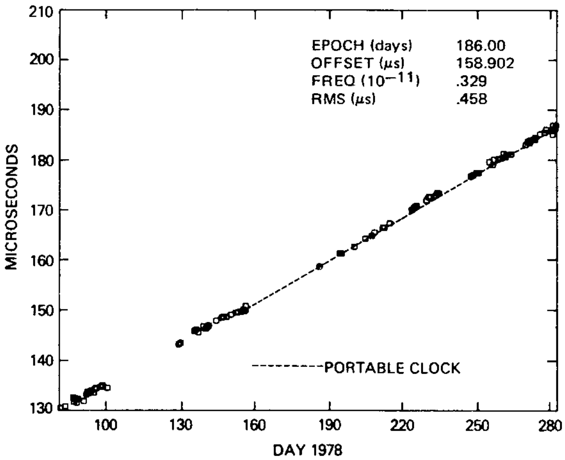

Fig. 7 — Time transfer results from the Division of National Mapping, Australia (USNOmMC1)-(AUS, DNM)

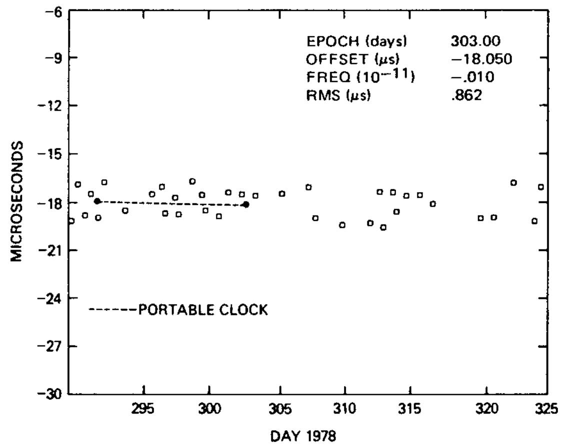

Fig. 8 — Time transfer results from RRL, Japan (USNO,MC1)-(RRL)

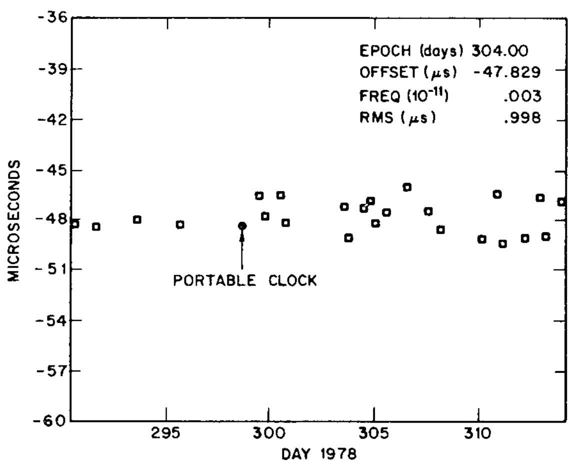

Fig. 9 — Time transfer results from NRLM, Japan (USNO,MC1)-(NRLM)

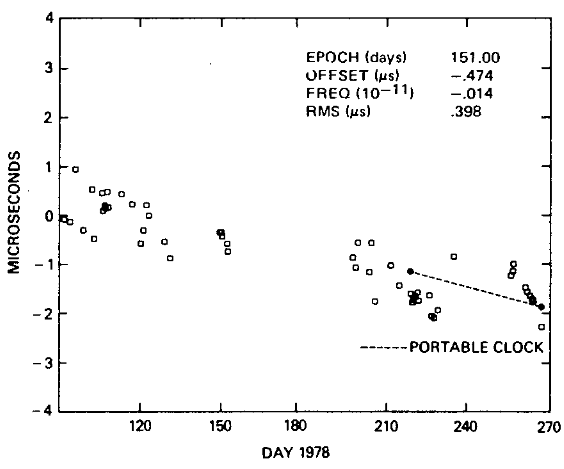

Fig. 10 — Time transfer results from NBS in Colorado, U.S. (USNO,MC1)-(NBS)

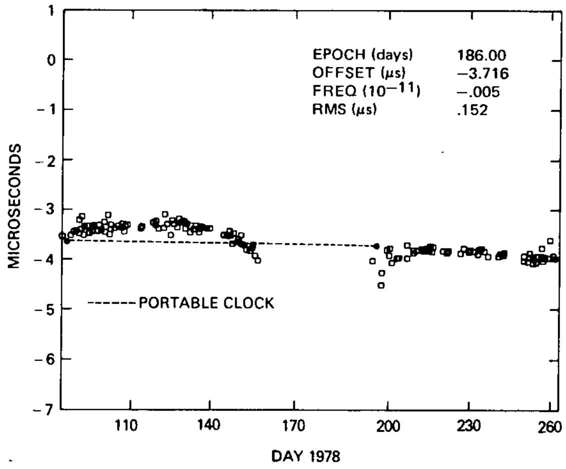

Fig. 11 — Time transfer results from National Research Council, Canada (USNO,MC1)-(NRC)

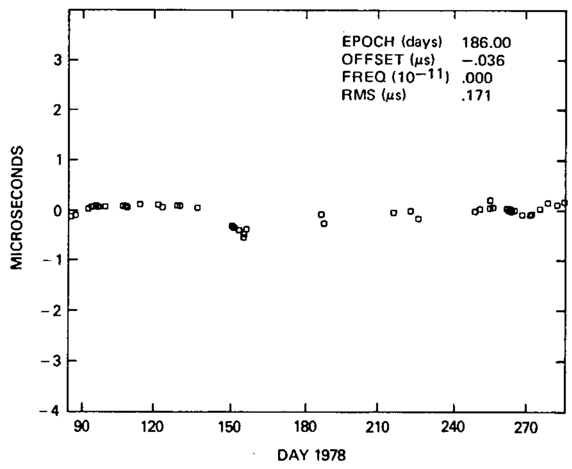

Fig. 12 — Time transfer results from USNO (USNO,MC1)-(USNO,MC1,NTS)

Table 1 presents the phase offset and frequency difference of each remote station clock against the USNOMC for a given epoch time which is nominally placed in the middle of the observed data span. In addition, the RMS of a straight line least squares fit to all satellite passes observed by the remote station is presented as a measure of the noise in the time transfer values.

Table 1 — NTS Time Transfer Results
UTC(USNO,MC)-UTC(remote, NTS)

Remote Site	Epoch (day 1978)	Phase Offset (μs)	Frequency (pp10^{11})	RMS (ns)
RGO (JP)	186	-160.734	-0.245	369
BIH (OP)	156	1.574	-0.006	318
CERGA	130	0.995	-0.049	324
IFAG	186	-10.277	-0.017	377
DNM (590)	186	158.902	0.329	458
RRL	303	-18.050	-0.010	862
NRLM	304	-47.829	0.003	998
NBS	151	-0.474	-0.014	398
NRC	186	-3.716	-0.005	152
USNO (MC1)	186	-0.036	0.000	171

From Table 1 it can be seen that the two Japanese remote sites (RRL and NRLM) exhibit a higher noise level than the other observing stations. These higher noise level measurements were the result of using predicted satellite position ephemeris. Further analysis will be performed using observed orbital trajectory.

Also plotted in Figs. 3 through 12 are the results of portable clock closures performed by personnel from the USNO. These portable clock closures are used as "truth" or absolute accuracy tie-in for the NTS results.

Figures 13 through 15 present time transfer results from the NTS remote observing station located at the Panama Canal Zone (CZ) site. Results in this data span were obtained with both NTS2 and NTS1 spacecrafts. The NTS2 data included observations available at both 335 MHz and 1580 MHz, allowing for a first order ionospheric delay measurement.

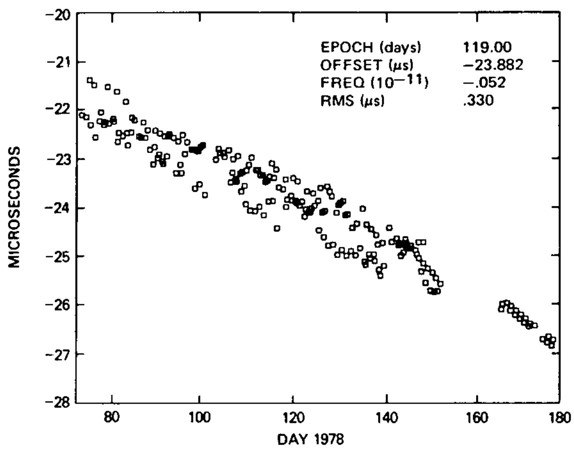

Fig. 13 — Time transfer results from Panama USNO,MC1)-(PMA)

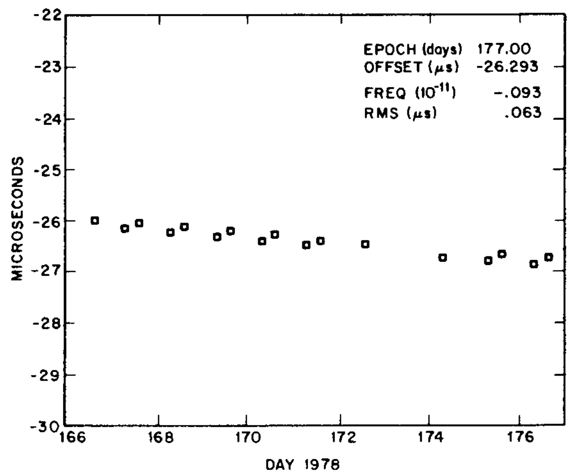

Fig. 14 — Panama results (12 day segment)

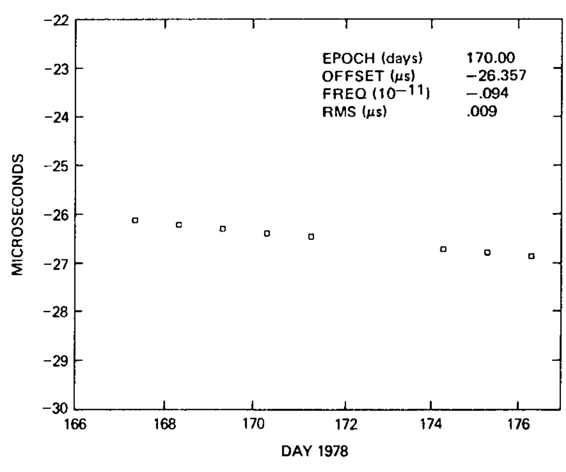

Fig. 15 — Panama results (same successive revolution)

The NTS1 data used only single frequency measurements at 335 MHz. Table 2 summarizes the CZ results in a similar fashion to Table 1.

Table 2 — NTS Time Transfer Results
UTC(USNO,MC)-UTC(CZ)

Epoch (Day, 1978)	Phase (μs)	Frequency (pp10^{11})	RMS (ns)
119	-23.882	-0.052	330
177	-26.293	-0.093	63
170	-26.357	-0.094	9

Figure 13 presents the entire data span consisting of both NTS2 and NTS1 measurements. Figure 14 presents only NTS2 data. The improvement in noise level was from 330 to 63 ns. This improvement was the result of two major advantages of the NTS2 spacecraft over the NTS1 spacecraft: first, the use of a cesium oscillator in space (NTS2) as opposed to a quartz oscillator (NTS1) and, second, the ability to correct for the ionospheric delay by dual frequency measurement (NTS2).

The additional improvement in noise level between Figs. 14 and 15 (from 63 to 9 ns) is the result of a systematic effect in the orbit determination method which corresponds to the 2 rev/day orbit configuration. Figure 15 uses observations obtained from the same side of the orbit each day. This noise level of 9 ns is considered to be indicative of results which can be attained in the full operational GPS constellation.

SYSTEM CLOSURE

Figure 12 presents the time transfer results for a receiver located at the U.S. Naval Observatory with a direct input from UTC(USNO,MC1). It can be seen that the noise level is 171 ns with an offset of -36 ns at the epoch presented.

Time comparisons for five of the major observatories are presented in Fig. 16. The inset in Fig. 16 presents the offset of three of the observatories to permit relative frequency comparison.

Noteworthy is the line for UTC(USNO,MC1) via NTS; a small slope on the order of a few parts in 10^{15} is present which is not statistically significant.

Table 3 presents the differences for the NTS1 time transfers with respect to the interpolated portable clock measurements. The average accuracy indicated by the portable clock is -0.06 μs. This table links the entire experiment to the absolute or "truth" values as determined by the DOD master clock.

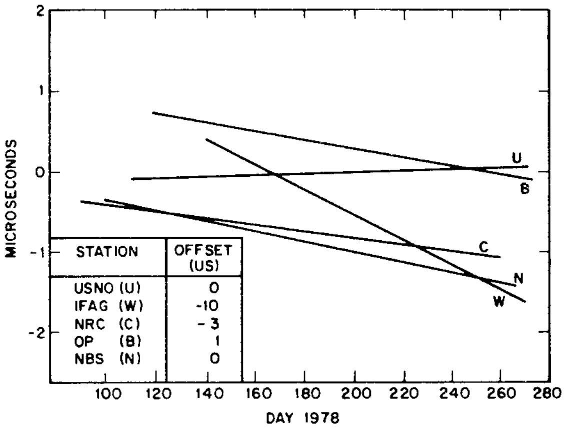

Fig. 16 — Time comparisons via NTS

Table 3 — Summary of Portable Clock Closures vs NTS Time Transfer Results

Station	Day (1978)	Portable Clock-NTS Time Transfer (US)
BIH	124	-0.57
CERGA	117	0.70
DNM	282	0.09
IFAG	199	0.03
NBS	221	0.19
NRLM	299	-0.53
RGO	115	0.44
RRL	303	0.13
USNO	186	0.04

CONCLUSIONS

The following items are summarized as a conclusion for the six nation time transfer campaign:

- Time transfers via NTS satellites of better than 1 μs accuracy have been demonstrated.
- Simulated single satellite GPS operation has been demonstrated.
- A 9 ns time transfer noise level over a 12-day span has been demonstrated as a possible best value of results.

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